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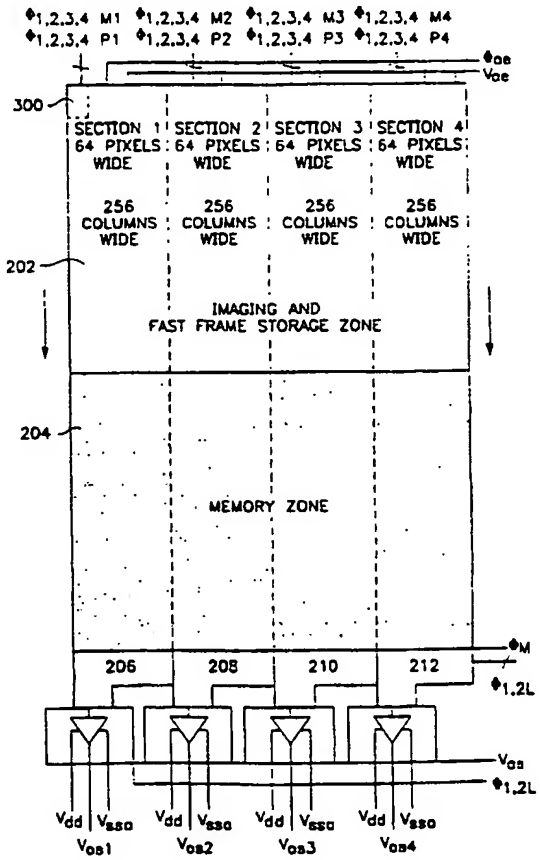
(54) Title: HIGH-SPEED CCD IMAGING, IMAGE PROCESSING AND CAMERA SYSTEMS

(57) Abstract

A solid state imaging array comprises an array of imaging photosites (202), having locally associated therewith a storage plurality of linearly sequentially operable analog memory cells (204) for storing sequentially captured image charge signals from the respective photosite.



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HIGH-SPEED CCD IMAGING, IMAGE PROCESSING AND CAMERA SYSTEMS

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of and priority from pending U.S. provisional application no. 60/017,035, filed May 3, 1996.

GOVERNMENT RIGHTS

The invention was made with Government support under Contract No. F08630-96-C-0066 awarded by the Department of Defense. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

The present invention relates generally to very high speed imagers, optical processors and electronic camera systems. More particularly, the present invention relates to electronic imaging systems which are capable of electronic image acquisition at image frame rates for example, up to one million image frames per second or more, as well as camera systems having extended compact analog storage capacity and/or processing capacity for acquired images.

There is a need for economical, ultrafast electronic imaging in a variety of scientific, commercial and military applications. Ultrafast electronic imaging sensors with up to million-frame-per second or more recording speed would be desirable for fundamentally enabling applications in particle physics, high speed chemical physics, industrial process control, biomedical applications, high resolution long range

imaging telescopes, and combustion flow fields. Unfortunately, current electronic detectors are not adequately sensitive, are relatively slow, or are expensive. For example, currently available high resolution electronic imagers, such as commercial CCD image sensors fabricated in silicon, have practical speed limitations on the order of several thousand frames per second for moderate to large frame sizes (e.g., at least 512 x 512 pixels) using a moderate number of output channels (e.g., up to 32). Some electronic imager frame rate speed improvement is possible with faster semiconductor devices, such as bumped GaAs output circuitry, but large frame rate increases will require new imager designs and geometries.

Conventionally, providing higher effective frame rates generally involves multiple imagers in multiplexed assemblies, or high speed film systems. In this regard, various ultrahigh speed cameras are based upon rotating prism/mirror assemblies which have an inherent mechanical time delay for start up and synchronization. These systems are large, inflexible and expensive, and have a variety of disadvantages.

For example, achieving high rotational speed of the mirror/prism assembly may require that the camera housing be purged with helium to reduce drag, and that the prism be made of relatively brittle beryllium, which may present a health hazard. Because of the mechanical inertia involved, such camera systems typically may be limited to triggering the event to be imaged (rather than being triggered), and typically provide only fixed interframe periods. The mechanical "spin up" time required for the camera to reach steady state makes it difficult to asynchronously trigger the camera based upon an event to be imaged. This also complicates

simultaneous triggering of multiple cameras for stereoscopic image capture. A user selectable interframe period combined with asynchronous triggering and fast gating control would permit capture of image data at high temporal resolution, and would also provide for stereo photogrammetry through the use of common, precision triggering of multiple cameras. It would be desirable to provide control of electronic image exposure separately from image capture frame rate, to permit more flexible matching of camera performance to image capture needs of a particular imaging application. However, at ultrahigh imaging speeds, independent control of shuttering and frame rate is difficult to provide together with high image quality.

Managing and storing the image output data from an ultrafast imager is also a current problem. For example, the image data capture and memory requirements for a 1K x 1K pixel camera operating at one million frames per second are enormous. The digital output image data rate of a 1K x 1K pixel imager operating at 1 million frames per second is one terabyte per second, which exceeds the capability of presently available digital storage systems.

SUMMARY OF THE INVENTION

A primary object of the present invention is to provide high-speed electronic imagers which are capable of high frame rates, such as image acquisition frame rates of up to one million frames per second or more. It is a further object to provide imagers and camera systems having novel and effective geometries, which facilitate efficient image acquisition. In addition, it is also an object to provide independent selection of frame rate and exposure time at such very

high frame rates. Yet another object of the present invention is to provide compact image storage capability for ultrahigh speed image acquisition.

Generally, the present invention is directed to electronic image sensors and electronic cameras systems which are capable of extremely rapid image acquisition, which also comprise high speed analog memory which is locally linearly associated with the imaging pixels of the high speed imager to store the images for a sequential plurality of acquired images.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other objects of the present invention will be apparent from the following detailed specification and the accompanying drawings, in which:

Figure 1 is a schematic block diagram of an embodiment of a CCD imaging system which utilizes an ultrahigh frame speed, low fill-factor CCD imager having a plurality of analog memory sites directly linearly associated with each photo-detecting site;

Figure 2 is a schematic plan view of one embodiment of an ultrahigh frame speed CCD imager which may be used in an imaging system such as that of Figure 1;

Figure 3A is a schematic top view of a portion of the imager of Figure 2 showing the spacing of active photosites with respect to the locally linearly associated memory storage cells;

Figure 3B is a schematic plan view of an alternative photosite and local memory geometry for the imager of Figure 2;

Figure 4 is an enlarged plan view of one of the photosite sections of the imaging array of Figure 2;

Figure 5 is a cross-sectional view of the

active photosite of Figure 4 taken along the horizontal, row direction of Figure 2;

Figure 6 is a cross-sectional view of the active photosite of Figure 4 taken along the vertical, transfer direction;

Figure 7 is a schematic top view of a 3-D stackable CCD sensor for an ultrafast imager with greatly extended analog memory directly associated with each imaging photosite;

Figure 8 is a 3-D stacked array of edge-imaging CCD sensors of Figure 7, with 1K buffer CCD channels, forming a compact 2D imager and 3-D analog memory system;

Figure 9 is a bump-mounted high speed CCD imaging system, with extended 3-D memory and/or processing capacity;

Figure 10 is a cross-sectional side view of a multiplexed SOS imager bump-mounted to a CCD wafer stack of the type shown in Figure 9;

Figure 11 is a schematic cross sectional side view of "pillar-recess" z- and y-axis alignment system for a 3-D image sensor and memory assembly such as that of Figure 8 or Figure 9;

Figure 12 is an ultrahigh speed stereo photogrammetry system using a plurality of simultaneously triggered ultrahigh speed cameras of the present invention;

Figure 13 is a schematic top view of a large format 4096 x 4096 storage cell/pixel CCD imager of full frame architecture which is adapted for ultrahigh speed imaging;

Figure 14 is a top view of an ultrahigh speed CCD imager with a four phase, high conductivity, parallel transport electrode bus system; and

Figure 15 is a schematic plan view of a

portion of an ultrahigh speed imager like that of Figure 3A, which is adapted for color imaging.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Generally, the present invention is directed to electronic imaging systems comprising an array of imaging photosites, having locally associated therewith a storage plurality of linearly sequentially operable analog memory cells for storing sequentially captured image charge signals from the respective photosite. Generally, the photosite array will desirably be two-dimensional array of at least 1000 active photosites regularly spaced in a two-dimensional array, and preferably may be configured as a regular two-dimensional array of at least 200,000 active photosites.

As indicated, the photosites each have a storage plurality of locally associated, sequentially operable analog memory cells. By "locally associated" is meant each photosite in the regularly spaced imaging array is directly connected electrically, such as by means of a CCD charge transport channel, to a storage plurality of at least 4, preferably at least 10, and desirably at least 64 linearly adjacent, electrically connected, sequentially transferrable, analog memory cells for each photosite. In addition, analog memory cells which are linearly locally associated with adjacent photosites are preferably adjacently positioned along a charge transport channel, such that the groups of analog memory cells which are locally associated with linearly adjacent photosites may also be transferred and read out sequentially. Desirably for highest speed operation, each photosite will be directly connected to at least 16 sequentially operable analog memory cells which can receive and store sequential charge signals

samples generated by the photosite at a rate of at least about 100,000 image samples per second and preferably at a rate of at least 200,000 samples per second, and most preferably, at least 1,000,000 image samples per second.

In one preferred embodiment, the group of analog image signal storage cells locally associated with each photosite are positioned linearly and sequentially along continuous CCD charge transport channels. The respective groups of analog image signal storage cells of linearly adjacent photosites are also positioned regularly and sequentially along each transport channel, so that the groups of image signals locally linearly associated with adjacent photosites may be read out of the transport channels in the same relative order. Desirably, all of the analog image storage cells may be shifted in parallel by a common transport electrode array, which will preferably be a three or four phase electrode transport clocking system.

Solid state CCD imagers conventionally utilize a regularly arranged array of photodetecting sites which produce and collect electrical charge when exposed to light. The amount of charge collected as a charge packet at the photodetection site corresponds to the intensity of the image and the integration time at the respective photosite location. These charge packets are then periodically transferred from the imager for digitization and further processing. The electronic imager photosites may be those utilized in a variety of photosensor systems such as a surface channel or buried channel charge coupled devices ("CCD") or other charge transfer device ("CTD"), a charge injection device ("CID"), or other photosensor array with which analog memory may be locally associated, as will be described in more detail. Although imaging photosites designed for the visible spectrum (e.g., 400-700 nanometers in

wavelength), such as silicon photodiode imagers are particularly desirable, the present methods and apparatus are also useful for imaging in the infrared (e.g., 0.7 to 15 microns), far infrared (e.g., 15-25 microns, or 15-100 micron wavelength), and ultraviolet (e.g., 100-400 nanometer wavelength) spectral ranges using silicon and other semiconductors such as III-V and II-VI materials. Various types of imagers are conventionally known and used over various such light wavelength ranges, and such imagers may be used to provide active photosite detectors at such wavelengths in accordance with the present invention. Charge coupled devices having buried channel charge transfer channels are particularly preferred because of their high speed operation and compact, sequential memory storage capability when employed with sensor geometries of the present disclosure. Such CCDs and associated camera drive and output electronics may be provided which are capable of very high frame rates, good pixel uniformity, and low noise when used with the imager geometries and operating methods of the present disclosure.

High speed Charge Injection Devices (CIDs) and CMOS photosites may also be used as electronic imagers, particularly for edge-sensitive photosites for 3-D stacks of imaging-memory chips as will be described. Such devices may comprise a linear array of photosensitive capacitor elements at the edge of the chip. Image readout may be performed by storing pixel image charge on one electrode and subsequently measuring the potential produced at the other electrode upon transfer of a charge packet to that electrode [see Zarnowski et al., SPIE Vol. 1447 (1991) Charge Coupled Devices and Solid State Optical Sensors II, pp. 191-201; Carbone et al., same SPIE Vol. 1447, pp. 229-237 for CID

imager description] for transfer into an extended CCD memory associated therewith. CTDs and CIDs may also be designed to perform image subtraction at the local pixel level on a charge mode basis at each pixel and other local neighborhood operations to provide the sampled image input. The photosite array may desirably have an effective fill factor of at least 75 percent when provided with a lenticular lens array or a lenslet array (e.g., diffractive optic or graded index).

It is desirable that design of the optical lens system and the electronic imager system be optimized to provide an appropriate balancing of resolution and aliasing. [C. S. Bell, Lens Evaluation for Electronic Photography, SPIE Vol. 1448 (1991) pp. 59-67]. In this regard, the limiting resolution of the image sensor and its inherent aliasing characteristics should best be designed to correspond with the characteristics of the lens system. A large amount of image information is lost in conventional imaging systems as a result of aliasing and/or blurring, even under optimal conditions. A minimum of two pixels is needed to detect modulated contrast in an image (although it is noted that each individual lattice pixel can produce an image edge enhancement value of the image at the image lattice position in accordance with the present invention), so the Nyquist frequency limit of the sensor array is approximately inversely proportional to twice the pixel repeat distance. Aliasing, an interference effect, may occur in imagers with image information at frequencies (spatial resolutions) higher than the Nyquist limit. Optical blurring is conventionally used with single frame imagers to reduce (or match) the lens spatial frequency resolution to that of the imaging system. For systems with color sampling, optical prefilters providing different amounts of blur

or smear for different colors may be utilized to optimize the lens system to the image at each wavelength sensitivity in accordance with conventional practice.

To provide increased resolution, imagers are conventionally used in an image scanning mode in which successive images are made after moving the imager by a pixel width in the image field ("step and repeat" or "fine scan" operation). Imagers used to increase image resolution in this manner are also intentionally designed to have low fill factors [J. Milch, "High Resolution Digitization of Photographic Images With An Area Charge-Coupled Device (CCD) Imager", Applications of Digital Image Processing, Proc. SPIE 697, pp. 96-104 (1986); Kontron Commercial Camera]. Accordingly, it will be appreciated that the methods and apparatus of the present disclosure may use systems in which the output frames of the photosensor sites of an ultrafast imager are shifted at high speed to form a higher resolution, composite image.

Illustrated in Figure 1 is an ultrahigh speed electronic camera system 100 which utilizes the overall high-density design of a relatively large conventional frame transfer or full frame CCD imager which has been modified in its photosite architecture by means of a specialized photomask, to permit high-speed image capture operation. Large pixel count CCD sensors such as that employed in the system of Figure 1 are typically designed for relatively low frame rate applications, such as from about 1 to about 60 image frames per second. While all of the columns of the image data may be conventionally shifted in parallel at high speed (e.g., over a million shifts per second along the vertical transfer registers), the conversion of the parallel data stream to serial output through a small number of output circuits (e.g., typically from 1 to 4

output channels, although 32 or more channels may be used for specialized systems) limits the frame imaging speed of such imagers. CCD imagers of up to 5K x 5K or more pixels (e.g., 25-60 million pixels) are conventionally available in a full frame architecture.

As schematically illustrated in Figure 1, the ultrahigh speed imaging system 100 comprises a lens 102, an electrooptical shutter and lenslet system 104, a high speed CCD image sensor 106, an electronic drive and a control system 108 for the CCD image sensor 106 and electrooptical system 104. The lens 102 may be any suitable camera lens for focusing a coherent or incoherent image or optical transform effectively at the focal plane of the imager 106. The optional electrooptical system 104 may include a high speed electrooptic shutter such as a Kerr cell, and/or a lenslet array to increase the effective fill factor of the high speed CCD image sensor 106, which will be described in more detail with reference to Figures 2-11. The electronic drive and control system 108 may also be of substantially conventional design, for supplying the drive and output signal processing for the imager 106, and yet provide image frame rates on the order of one million frames per second for a continuous sequence of frames, when used in conjunction with the imager modifications which will be described in connection with Figures 2-6. The CCD drive and control system 108 generally comprises vertical (parallel) shift register drivers, horizontal shift register drivers, data output A/D conversion and memory circuitry, CCD biasing circuitry and other circuitry appropriate to controlling a particular CCD imager (see "CCD PRODUCTS" 1996, the 1996 product sales catalog of Thomson-CSF Semiconducteurs Specifiques, for examples of CCD imagers and connection pins, register drive and readout voltage

and timing diagrams, and CCD camera/driver kits, which is incorporated by reference herein)

Illustrated in Figure 2 is the large format frame transfer 1024 x 1024 CCD imager 106, which features a parallel architecture which is easy to drive and to collect the output data. The imager 106 has 1024 x 1024 closely adjacently packed photosensitive pixels of 14 microns x 14 microns cell dimension, repeated in a square array. The 1024 x 1024 pixel imaging zone is positioned along conventional vertical shift registers next to a light-shielded frame transfer memory zone. In accordance with this conventional design, the entire 1024 x 1024 pixel image frame may be rapidly transferred to the shielded frame transfer zone at a parallel frame transfer rate of about 1.3 Mhz, or less than 0.001 second to transfer the 1024 lines of the image from the image zone along the vertical transfer columns of the device. The shielded frame transfer memory zone has four parallel outputs running at 20 Mhz maximum data rate each, which provides full chip output rates as high as 60 Hz (made of 1024 x 1024 memory cells) with 10-12 bit gray scale resolution. Other specific on-chip capabilities include anti-blooming and exposure time control. The illustrated device 106 is a commercial THX 7887A CCD imager of Thomson-CSF Semiconducteurs which is conventionally operated at up to 60 frames per second, but which is modified by a specialized light shield, and the method of operation, to provide a structure for ultrafast imaging at a frame rate in excess of one million frames per second.

As shown in Figure 2, the CCD imager 106 is a square frame transfer area array CCD imager which is specially designed to capture up to 16 images of 256 x 255 pixel image frame size, at frame rates up to approximately 1.3 megaframes per second. The special

modification comprises a metal mask over the imaging section which is opaque except for a precisely aligned pattern of pixel openings which permits the ultra high-speed operation of the imager. The imager 106 itself comprises an approximately 1 megapixel imaging zone 202 formed by 1024 x 1024 square pixels (14 microns x 14 microns) arranged along vertical CCD shift registers (in the direction of the arrows) and a memory zone 204 having the same storage capacity, allowing for simultaneous and controlled readout of the memory zone analog data. The image zone 202 comprises 1044 horizontal lines (rows), including the 1024 pixel lines and five dark reference lines at the top and five dark reference lines at the bottom of the array 202. Supplementary lines are used as isolation lines for dark reference integrity. The optically inactive memory area 204 has the same number of lines as the imaging zone.

In order to increase the output rate of the memory zone 204, the imager has four output sections 206, 208, 210, 212, each of which receives the analog charge packets from one fourth (256) of the 1024 CCD transfer columns. Accordingly, the imaging and fast frame storage zone 202 and the memory zone 204 may be regarded as being functionally divided into four sections of 256 CCD transport channels each. The imaging and fast frame storage zone 202 itself is specially designed to permit ultrafast acquisition of sixteen frames of 256 x 255 pixel image size, by specialized masking of the otherwise actual imaging zones of the imager, together with high speed transport clocking of the CCD transport channels of the imager.

A plan view of a portion 300 of the imaging and fast frame local analog memory storage zone 202 of the CCD imager 106 is shown schematically in enlarged form in Figure 3A. As shown in Figure 3A, the otherwise

active pixel cells 302, 304 are arranged in conventional vertical CCD transport channel columns oriented in the direction of the arrows, toward the memory zone 204 (not shown) of the frame transfer imager 106. Each of the cells 302, 304 would ordinarily be active photosites for imaging through the respective four-phase vertical transport register electrodes of the imager 106 in accordance with conventional practice (see Figures 4-6). However, the otherwise conventional CCD imager 106 is modified by a specialized opaque metal mask 306 shown as a dark trellis pattern, which covers the majority of the photosites 304.

In the illustrated embodiment 300, only one sixteenth of the cells are not masked by the opaque aluminum layer. The pixel openings in the mask layer 306 which form the active photosites 302, are arranged regularly over the surface of the imager (spaced approximately 4 cells apart vertically and horizontally) but angularly displaced with respect to the longitudinal direction of vertical transfer registers 310, such that charge collected at a photosite 302 may be linearly and serially shifted 15 times vertically along the transport channels 310 through the "opaque" storage cells 304, before reaching another active photosite 302.

As shown in Figures 3A and 3B, the active photosites 302 are regularly arranged with respective predetermined spacings along two axes, at least one of which is rotationally displaced with respect to the longitudinal direction of the vertical (parallel) transfer registers 310 of the CCD 106. This permits the linear shifting of image data from each photosite to progress a multiple of the predetermined spacing between the active photosites 302 generally along the transport channel direction, before encountering another active photosite 302. The predetermined spacings will

generally correspond to a whole number of pixel/memory cells 302, 304 in the direction of the respective axis, and may be different for each axis of the photosite array.

As shown in Figures 3A and 3B, the multiple of the spacing along the transfer channel direction is a function of the integer cell spacing along the other axis of the photosite array. Accordingly, the photosite and storage cell arrangement shown in Figure 3A is capable of capturing and storing 16 images. If the photosites were spaced apart by 8 cell units along each array axis, the imager would be capable of capturing and storing 64 images, but the number of active pixels in the imager would be one fourth of that with 4 cell spacing.

Because the charge packets may be transported very rapidly along the transport channels (e.g., at four phase clocking speeds of over 1 Mhz in accordance with conventional frame transfer operation of the THX 7887A CCD imager and camera drive circuitry), the imager design 300 can accomplish extremely rapid imaging while transporting the image charges. The 16 successive images are interleaved as shown in Figure 3, with cells 16 being the first image, cells 15 being the second image, back to cells 1 being the most recent image. The 16 images captured and stored in the imaging and fast framing storage zone 202 may be clocked to the memory zone 204 for subsequent readout, using conventional electronic camera CCD drive and output circuitry for the Thomson 7887A CCD imager chip.

In operation, the ultrahigh speed camera system 100, under control of the electronic drive and control system 108, may initially have shutter 104 in closed position, and the four phase transport electrodes will be in quiescent, nontransfer mode which is

receptive to image capture. At least two, and preferably three of the four electrodes are placed at electron depletion potential, to maximize the image signal charge storage capacity of the photosites. Preferably, prior to image capture, the antiblooming gate and drain are activated to remove unwanted image signal.

To capture an image at high speed in a relatively simple mode of operation, the system 108 opens the shutter 104 and/or activates the illumination of the event to be imaged, and drives the four phase transfer electrodes of the vertical registers up to 16 cycles of parallel, vertical transfer along the vertical registers 310 of the imaging zone 202, at a vertical shift rate corresponding to the desired image capture rate, which may be at a rate of at least 50,000 frames (or vertical shifts) per second, up to one million or more frames per second. The initiation of the transfer cycling may be precisely triggered within less than one quarter of the cycle time, in accordance with conventional imager drive practice. The antiblooming and drain gates are deactivated during imaging.

The THX 7887A imager 106 is designed to operate at vertical shift rates of up to about 1.3 million cycles (vertical shifts) per second. The maximum number of images which may be captured at high speed is limited to the number of memory cells which are locally associated with each active photosite, here 16.

The vertical clock shift cycles are then stopped, while maintaining the image data in the respective storage cells. The shutter or scene illumination may be then be turned off, and the composite images clocked to the frame store zone 204, from which they may be read out at high precision in the conventional manner. The individual images, having a

precisely known location in the composite image, may be easily "sorted out" or separated in digital memory in any appropriate manner. While the imaging may be carried out as previously described to produce uniform frame rates in which the exposure time is the reciprocal of the frame rate, other modes of image capture may be used.

For example, the exposure time of each image may be separately programmed and cycled, if desired. In this regard, with reference to Figure 3A, the first transfer cycle time could be one microsecond, the second through fifth cycle times could be 5 microseconds, and the remaining sixth through sixteenth cycle times could be 10 microseconds, with corresponding exposure times.

Similarly, the camera may be operated to provide independent control of frame rate and exposure time, such that the image exposure times may be effectively less than the reciprocal of frame rate. For example, by clocking the CCD vertical transfer to shift the first image at a first rate (e.g., one microsecond) then hold the second image for a predetermined exposure time (e.g., 9 microseconds) before shifting the image again in one microsecond, followed by an image shift for the third image at the first (one microsecond) rate, and the fourth image at the 9 microsecond exposure time, etc. By alternating images at a first exposure time with images at a second exposure time, alternate images may be discarded to provide the desired exposure control. In the example given, the effect of 100,000 frame per second imaging with either one microsecond or 9 microsecond exposures is provided in a completely programmable and user selectable manner. The penalty is that approximately half of the images which are discarded, and the corresponding storage area of the imager is not directly utilized.

However, this is a very powerful feature of the present disclosure, which is programmable via control of imager clocking, and does not require custom imager chips, such as very large interline transfer CCDs with independently gated photosites.

The active photosite arrangement of Figure 3A has rows of photosites arranged to permit extended linear shifting of charge packets in linear memory cells locally associated with the active photosites, but this arrangement is not a square pixel array. Illustrated in Figure 3B is an active photosite distribution which does present a square active pixel array, albeit one in which both axes of the array are rotated with respect to the vertical charge transport channels 310. It should be noted that in this arrangement, in which successive active photosites 302 are spaced approximately four cells apart but rotationally displaced both horizontally and vertically with respect to a rectangular grid aligned with the CCD transport channels (in the arrangement of Figure 3A the active photosites are only rotationally displaced in one direction), that the imager can store 17 rapidly successive images, rather than 16 images.

Similar patterns may be provided to further increase the number of successive images which may be successively captured and stored in analog memory cells locally adjacent the active photosites. For example, an array of regularly spaced photosites like that of Figure 3A, but in which the active sites are separated by eight cells, will provide an array in which an analog charge may be shifted 64 times before it encounters another active photosite, and accordingly the system can capture 64 successive images at extremely fast image frame rates.

A similar square array like that of Figure 3B,

in which the active photosites are displaced in both the horizontal and vertical directions and spaced apart approximately eight cell units, will increase the number of successive image frames to 65. This also results in approximately one fourth of the resolution in each image frame, given the same number of cell units, as previously discussed. For this reason, it may be desirable to use even larger imager sizes, such as 2024 x 2024 or 4048 x 4048 cell imagers, in order to provide for extended image frame numbers while maintaining a desired degree of image resolution.

The imager 106 is used to output the 16 (Figure 3A) or 17 (Figure 3B) image frames stored in the frame memory output area 204 at a rate of up to sixty frames per second (fps), in the conventional manner for this chip. This frame rate is obtained through four parallel area arrays of 256 (V) x 1204 (H) pixels each, each ended by its own serial CCD readout register, 206, 208, 210, 212. Four parallel output amplifiers deliver the data signals to the control unit 208 at the maximum data rate of 20 Mhz (4 X 20 Mhz for the whole array). The output data is digitized and stored in digital memory in the control unit 108, where the individual images are separated.

For 1 million frame per second operation the electronic image of the photon flux impinging on the unmasked photosensitive areas is sampled by the pixel array during a time period which is very short. Electronic shuttering is available on the chip, but is not necessary during this period. However, if it is desired to operate the chip at slower frame rate, this can be done by clocking the anti-blooming gate to the shuttering level voltage, then dumping the unwanted photogenerated charges towards the anti-blooming drain. After the 16 frames are captured, at a continuously

uniform rate, or at a programmed varying rate, the composite electronic image may be quickly shifted from the imaging area towards the memory area at very high speed. During this period, the electrooptic shutter 104 may be turned off (rendered opaque), the illumination may be turned off, or on-chip electronic shuttering may be used when available. In this way, the charge packets each representing an exposed image pixel of one of the 16 images taken in rapid succession, are all transferred in the same order to the memory zone 204.

The memory zone 204 can be shifted independently of the imager zone, a line by a line, into the four serial CCD registers, each of which is terminated by an output node (floating diode). These output nodes are simultaneously reset to the reference voltage level VDR prior to charge packet receipt from the next CCD serial shift register stage. Their potentials are permanently sensed by a double stage source follower nMOS amplifier, and sampled charge packets in the CCD register are then clocked continuously, stage by stage, towards these nodes. Each output amplifier accordingly delivers the electronic charge information of a quarter of an image line-256 pixels-, in the serial typical waveform of a CCD output floating diode signal, for the 16 interleaved ultrafast images stored in the frame.

As shown in Figure 4, the unit cell pitch of the photosite and storage cells 302, 304 is 14 microns x 14 microns, and includes the anti-blooming structure and sensitive area which serves as a photosite at the mask openings. In this frame transfer architecture, the sensitive area 302 acts also as the locally associated analog memory for the active photosite, as the inactive storage cell units 304 for those cells which are masked, and as the transport medium towards the memory zone--see Figure 2. The design of this area should optimize the

"fill factor" (FF) of the pixel and its light responsivity, its saturation charge, the efficiency of the anti-blooming drain, acting also as a dump drain for integration time control (electronic shutter)-, and the transfer efficiency at high speed. The fill factor of the individual active photosite is still relatively small compared to the area of the imaging zone 202 because of the masking utilized to permit high speed operation. The effective active photosensor area may be increased by lenticular microlenses and/or refractive lenslet arrays, such as may be included in the optical component 104 of Figure 1. By providing, for example, a refractive microlens array of individual lenses of area approximately 10 to 15 times the area of the active photosites 302, which are respectively each perpendicularly above and focused on each of the active photosites, the effective fill factor may be increased to at least 80 percent. Increasing the effective fill factor, and the corresponding effective light efficiency with respect to the image is particularly important for ultra high imaging speeds, which tend to require high light intensities to permit collecting enough light to register a useful image in any event.

The cross-view of the pixel is shown in Figure 5. As shown in Figure 5, the pixels have a lateral overflow drain structure which may be used in the high speed operation of the imager, as discussed previously. The anti-blooming structure is shared between two neighboring pixels, acting as the pixel separation on the both horizontal pixel sides. This structure is made of half a drain and one gate on each side of the pixel (anti-blooming drain and anti-blooming gate), that is one drain and two gates per pixel pitch. The potential barrier controlled by the anti-blooming gate has to be set to the anti-blooming potential level so that

exceeding charges in the CCD channel spill out first into the anti-blooming drain instead of blooming up and down in the neighboring pixels.

The photosensitive and transport area is located in the CCD part of the cell units. It is made of a set of four overlapping gates as shown in Figure 6. This allows a four phase transfer operation during the image shift towards the memory zone. This transfer mode is used for its good charge handling and charge capacity, largely greater than the three phase or two phase mode. As an example, the saturation level of this four phase pixel-cell unit is 210,000e-, when it would be only 140,000e- for the three phase mode. Moreover, the four-phase structure allows charge collection and integration in a potential well controlled by three gates-about 10.5 microns long in the 14 microns pitch-, longer than the two-gate well control-9.3 microns long for this pixel-when using the three gate architecture, which improves the optical modulation transfer function of the sensor.

Each 14 x 14 micron square imaging pixel uses a three level polysilicon MOS gate structure on a buried channel phosphorus implantation in an epitaxial p/p+ silicon substrate. The anti-blooming overflow drain is phosphorus implanted and self-aligned on the two controlling gates. Owing to the 1.5 microns design rule CCD technology, this anti-blooming structure layout is only about 5.5 microns wide. The pixel aperture, at the Si/SiO2 interface level, is estimated as 10.3/14, providing a fill factor of 0.74 for the active cell. This value is the minimum fill factor of this pixel for the blue wavelength, as blue photons are absorbed in the first hundred nanometers under the interface. For red light, the fill factor is larger, as the internal pixel separation inside the silicon is thinner than it is at

the Si/SiO2 interface, the internal electrical fields expanding under the anti-blooming gate, to increase the fill factor for these wavelengths.

In the memory zone, vertical isolation between pixels is made of thick oxide on p+ boron implant instead of the anti-blooming device. This part of the circuit uses then only two level polysilicon CCD gate structure. The area not used by the anti-blooming structure permits the CCD stage length to be reduced to 13.2 microns versus 14 microns in the image zone. This achieves even a greater charge handling capacity than in the imaging pixel in order to have no saturation limitation in this area. This area is terminated by a specific gate controlling the charge transfer into the readout registers.

In order to provide high speed charge transfer, interconnections are used to contact the pixel gates with aluminum rails and aluminum buses run from the top of the array, driving both the image and the memory zones, on the anti-blooming structure in the image area, and on the thick oxide region in the memory zone.

Because the entire array has a relatively large capacitance for each clock of the photosensitive array (Pi) of the whole imager 106 is in the range of which is difficult to drive through classical clock drivers such as the 0026 series. Accordingly, the array is divided into four sub-arrays of 256 columns, so that each can be readily driven at high speed by conventional clock drivers. This results in a typical frame transfer frequency of up to 2 Mhz, which is compatible with very fast imaging operation.

The memory zone is provided with one CCD readout register for each of the four 256 x 1024 pixel sub-arrays. Each readout register is made of 256 stages

devoted to receive in parallel the signal charge coming from the associated pixel sub-array, plus 15 extra-stages needed for driving the charge towards the output amplifier, usable as electrical reference pixels as well. This structure is repeated four times along the last 1024 pixel line of the memory area.

The four CCD readout registers use two polysilicon two phase structure, with buried channel, with the same 14 microns pitch as the imaging and fast framing zone 202. They are driven four in parallel by two clocks (L), and terminates each 9X gate VGS, stopping on an output floating diode. A channel turn is used to allow the tapped structure to operate without disrupting the 14 microns pitch. The readout design structure is the classical "Floating Diode Readout" (FDRO), which uses an output n+/p diode as a charge detector after reset through the clock (R) to the reference positive voltage VDR. Charge packets coming from the output register are dropped out one by one by the last clock (2L) into the floating diode well, over the output gate BGS, lowering the floating potential of that diode. This voltage is sensed by the respective output amplifier. Four output amplifiers are used for the circuit, to deliver the video signal coming from the four output registers. They are designed for a bandwidth of 95 Mhz and low noise operation. Each of them is a double stage source follower NMOS amplifier.

The output CCD registers are driven at 20.8 Mhz, and the device may be read out in a progressive scanning mode with very high dynamic range (up to 80 dB w.r.t. noise level in darkness). The integration time may be set from zero to 15.9 ms., leading to the memory output rate of one memory block consisting of 16 sequential subimages, per 16.6 ms. The imager zone frame transfer is operated at up to 1.3 Mhz, and the

applied voltages are set to the nominal value. Additional features of the imager, other than the high speed specialized masking and imaging process, are described in "THX 7887A: A New High-Frame-Rate 1024 x 1024 Pixel CCD Sensor," G. Boucharlat et al., SPIE Vol. 2273, pp. 255-263; see also, J. A. Cortiula, "THX 7897M: Capteur CCD 2048 x 2048 Pour Applications Astronomiques," OPTO 93, Paris, May 11-13, 1993.

The system of Figures 2-6 is based on the conversion of an existing frame transfer imager, in order to minimize the design expense of creating new masks and other capital investment, because the existing design can be used with the addition of an additional metal or other opaque mask to produce the desired, restricted, active pixel pattern. Similarly, other existing imagers may be modified by applying a mask, to make the most cost-effective initial production of ultrafast imagers. For example, interline transfer imagers, full frame imagers, and frame transfer imagers may be utilized. The commercially available 2024 x 2024 pixel Thomson CSF 7899 full frame imager is useful because of its large number of pixel cells, for making masked pixel designs of sparsely distributed active pixels. Such arrays were previously described as the arrays in which the active pixels are nominally separated or displaced in both column and row directions by 8 pixels, producing an imager which can store 64 or 65 ultrafast sequential images. Use of gated photodiodes, which are used in many imagers such as those of the interline transfer type and which are not in the charge transport channel, permits the most effective electronic shuttering, to initiate imaging during the ultrafast sequence of imaging but to stop the imaging during the imager readout. Ultrafast CCD imagers may also be designed to take full advantage of

architectures in which the active photosites (preferably not in the charge transport/memory cell channels and are subject to electronic shuttering) represent a very small percentage of the area of the imaging array, and the analog memory cells associated therewith represent the major component of the imaging array. An example is the high speed system described in U.S. application no. 08/423,654, filed April 17, 1995, for High Speed CCD Imager, which is incorporated herein by reference.

As illustrated in Figure 12, two or more ultrahigh speed cameras 1201, 1202, 1203 may be integrated into a stereo photogrammetry system, through the use of a common, high precision trigger 1201. The cameras are adapted to receive a common triggering signal, which, together with a common frame gating and exposure program, provides synchronous stereo imaging from multiple cameras. The cameras 1201, 1202, 1203 may be fast framing solid state cameras with substantially film quality imagery, which are adapted to provide variable interframe periods from 100 microseconds to 100 ns., with temporal gating capability down to 1 -10 ns. With pulsed laser illumination, the cameras may provide 10-12 bit gray scale images with at least 4, and preferably at least 16 frames of on-chip image storage.

Figure 13 is a schematic top view of a large format 2048 x 2048, and preferably 4096 x 4096 storage cell/pixel CCD imager 1206 of full frame architecture which is adapted for ultrahigh speed imaging for the camera system of Figure 12. The full frame CCD imager 1206 has a large format of at least 2048 x 2048 storage cell/pixel size, and more preferably at least 4096 x 4096 storage cell/pixel size, which features a four-port parallel output architecture for high data throughput. It may be designed and fabricated substantially in accordance with the THX 7899M full field image sensor

which is commercially manufactured by Thomson CSF Semiconducteurs Specifiques, Orsay, France.

Electrical stimulus for the CCD imager is depicted in Figure 13 and is as follows:

Φ 1,2,3,4 P(n)	The low speed four-phase clocks used for vertical image shift (clock rate = 1-10 Mhz)
Φ_{ab}	The antibloom gate clock
V_{ab}	The antibloom sink bias voltage
$\Phi_{1,2L}$	The high speed two-phase horizontal image shift clocks (clock rate = 20 Mhz)
Vdd	On-chip amplifier bias
Vssa	On-chip amplifier ground return
Vos(n)	Video output

The preferred imager itself comprises an approximately 16 megapixel imaging zone formed by 4096 x 4096 square pixels (e.g., each pixel or storage cell measuring 14 microns x 14 microns of which approximately 10 microns x 14 microns is active photosite area) arranged along vertical CCD shift registers (in the direction of the arrows), allowing for simultaneous and controlled readout of the image zone analog data.

In order to increase the output rate of the device, the imager has four output sections, each of which receives the analog charge packets from one-fourth (e.g., 1024) of the 4096 CCD vertical transfer columns, as shown in Figure 12. During conventional operation, the imager would integrate the optical image input over each of the pixel cells in the image area for a predetermined period of time under control of the camera control system. The imager would be externally shuttered. Then the image would be shifted down vertically one row at a time until the entire image is directed through the respective output amplifiers.

The special light shield modification comprises a metal mask of the type illustrated in Figure

3A or Figure 3B over the imaging section, which is opaque except for a precisely aligned 1024 x 1024 pattern of pixel apertures. In conjunction with a customized CCD clocking sequence, this specialized light shield mask, permits ultrafast acquisition of 1024 x 1024 subimages within the larger 4096 x 4096 array. By applying the specialized masking to the otherwise active pixels in the imaging zone, local image storage regions are created which eliminate the need to clock the entire image (4096 rows) out of the array before capturing the next image. In fact, appropriate design of the metal mask allows the 1024 x 1024 subimage to shift its data into a memory zone and prepare for the next image capture after only one vertical shift cycle.

Since a vertical shift can be carried out in as short a time interval as 100 ns., this means that the 1024 x 1024 subimager is capable of capturing new images at a rate of 10 MFPS until the locally created memory area has been exhausted. For a 1024 x 1024 subimage in a 4096 x 4096 image array, approximately 16 ultrahigh speed sequential subimages may be captured and stored for high precision, slow readout.

Accordingly, the photosite and storage cell arrangement shown in Figure 3A is capable of capturing and storing 16 images of approximately 1K x 1K image size. Because the charge packets may be transported very rapidly along the transport channels (e.g., at four phase clocking speeds of up to 10 Mhz), the subimager actually captures a new image at up to a 10 million frame per second rate. The 16 successive images are interleaved as shown in Figure 3, with cells 16 being the first image, cells 15 being the second image, back to cells 1 being the most recent image. In conventional operation, the 4,096 x 4,096 imager would require 4,096 vertical shifts in succession to read out an image

frame.

In the high speed (10 million frames per second) mode of operation, this clocking pattern is stationary until initiated by the triggering signal. A conventional four phase clocking pattern is then initiated which provides a predetermined number of vertical parallel shifts which does not exceed the number of storage cells which are locally linearly associated with each photosite (here 16, including the photosite). Within one cycle the clocking pattern is then abruptly stopped so that the subimages remain stored without overlap from image signals from adjacent photosites. The camera is then effectively shuttered, and remains in an idle state until readout is initiated.

In some circumstances, it may be desirable to capture a burst of images at 10 million frames per second, pause for a length of time, capture a 1 million FPS burst, pause, capture at 500 KFPS, etc., as previously discussed. For example, the user might want to capture 6 frames at 10 million FPS, pause for 1 ms., capture another burst of 6 at 1 million frames per second, pause for 10 microseconds and then fill the remaining memory buffer at 500 KFPS. This mode of operation may be provided as a programmable feature of the high speed solid state camera systems of the present invention.

The transport electrodes of such a large image sensor are comparatively narrow and long, leading to relatively high resistive load in addition to the high capacitive load resulting from the large area of the imager. It is difficult to drive such a large image sensor at a high frame rate significantly in excess of one million parallel (vertical shift) cell transfers per second, without charge transfer inefficiency and other problems. To provide an imager structure for ultrafast

imaging at a frame rate in excess of five - ten million frames per second, the imager architecture may be modified by applying a custom light shield, utilizing a specialized clocking scheme, and by adding relatively large strapping or bus electrodes atop the light shield to facilitate high-speed operation. The strapping electrodes, in turn, are made possible because of the light shield and imager operation, because if a high proportion of the imager were used for photosites, the strapping electrodes would interfere with imaging at the photosites.

As illustrated in Figure 14, the large strapping electrodes are provided atop and insulated from the metal mask applied to the imager. The wide buses are connected periodically to each of the respective same-phase transport drive electrodes by vias in accordance with conventional integrated circuit fabrication practice. Because they have a much smaller resistance, and a much smaller length-to-width ratio, very high speed operation is facilitated at higher transfer rates than those permitted by the four phase polysilicon transport electrodes alone, which have a width of only about 2.5 microns and are thin enough to permit imaging therethrough in the pixel cells.

As illustrated in Figure 14, the space between the active pixel sites may advantageously be used for additional, relatively wide, highly conductive transport electrode busing, which can be used to apply the transport clock signals at periodic intervals (vias) to the underlying transport electrodes. Because these electrodes may be metallic and up to ten or more times as wide and at least 10 times more conductive, as the polysilicon or silicide pixel transport electrodes (four to each pixel site in a four-phase transfer electrode structure such as used in the systems of Figures 1 and

13), the resistive drive load may be greatly decreased, and the transport clock frequency may be increased to 5 - 10 million frames per second, while retaining substantial pixel uniformity and charge transfer efficiency.

To increase the light sensitivity to the final camera (since much of the active pixel area has been shielded from light), a lenslet array is mounted over the masked CCD array to bring the fill factor up to at least 60%, and preferably at least about 85%. For example, in the pixel pattern of Figure 3A, a photoactive aperture exists only once every fourth pixel. Assuming a basic pixel pitch of 14 microns, the fill factor would be about 1/16 or 6%. By applying lenslets over and focussed on each of the sensitive apertures, which are about 55.5 microns in diameter (with a 1 micron spacing between lenslets for manufacturing purposes), the effective fill factor is brought up to over 90%.

A significant advantage of this solid-state architecture is that after acquiring 16 images at up to 10 million frames per second, the "store" of captured frames may be read out at relatively low data rates allowing for the very high dynamic range. Because readout data rates can be kept to relatively low rates such as 20 megapixels/second, standard (commercially available) high performance readout circuitry including analog-to-digital converters and frame grabbers can be used for data acquisition, rather than expensive ultrahigh speed data capture systems.

High speed temporal gating which is independent of the frame rate may be accomplished by pulsed laser illumination and/or by high speed gated intensifiers. Copper vapor lasers exist with pulse durations on the order of 1 ns. gating. While this

"gate" duration is sufficient for most high speed imaging, the repetition rate of the pulsed laser source is typically limited to 10's of kilohertz. Gated intensifiers offer an alternative path which provides not only temporal gating, but image intensification (a significant advantage in high speed imaging applications).

Intensifiers with high resolution of up to 641 p/mm. can be achieved on an 18 mm. intensifier cell which provide repetition rates in excess of 10 Mhz and gating resolutions on the order of 1-5 ns.

The cameras of Figures 1 and 12 are designed to operate in wideband panchromatic mode, or in monochromatic mode with an external color filter or light source. Illustrated in Figure 15 is the masking for a color version of an ultrahigh speed imager. In the imager 1500 of Figure 15, a mosaic of microscopic red color filter dots 1501, microscopic green color filter dots 1502 and microscopic blue color filter dots 1503 are fabricated on top of the imager array before applying the light shielding mask as shown in the Figure. As shown in Figure 15, 3 columns are utilized to store image data for each RGB pixel array. The pixels may be rectangular (e.g., with a length to width ratio of up to 3:1), to make the overall RGB pixel area more square. A large microlens over each pixel is used to focus the light from a circular area onto the RGB pixel pattern.

The rate of image data captured by very high speed imaging systems such as the two dimensional array illustrated in Figure 2 limits the number of frames and image resolution which can be accomplished by such two dimensional arrays.

In order to provide for additional image memory locally associated with each active photosite,

the present invention is also directed to CCD imager systems which utilize three dimensional stacked layers of parallel edge-input CCD imaging arrays such as an edge-sensitive CCD 702 shown in Figure 7 to form an integral imager, memory, and output or processing system such as a system 802 shown in Figure 8. Such stacked arrays can store a higher number of image frames, and may also process the sequential images acquired at such high speeds to compress or selectively simplify the data output requirements of the system. Imager and camera systems based on extraordinarily compact imager/memory stacks formed by such chips can provide significantly enhanced performance. The imager/memory stack may be assembled by stacking individual CCD memory chips to form an imaging face and an output face (Figure 8). Each individual memory chip may be driven at 1 - 10 Mhz, which is relatively slow for CCD memory operation, but which provides ultrafast imaging operation because of the fully parallel processing design. The chips have a linear array of edge-sensitive input pixels, each of which is clocked to its own CCD memory channel, which may be 1,000 or 2,000 memory cells or more long. The memory channels are multiplexed and clocked to one or more conventional high speed output amplifiers, for clocking the image data off-chip, as shown in Figure 7.

When the edge-sensitive CCD memory chips of Figure 7 are stacked vertically, the linear photosites at the edges of each chip form a 2-dimensional pixel array at the imager face. In addition, the associated CCD memory channels form a compact, very high-density 3-D memory which operates fully in parallel to receive the data which is clocked out from each corresponding edge-photosite at 1-10 Mhz. As indicated, the imaging face is formed by the edge-sensitive linear pixel array on each chip, which may include optical waveguides and

lenslets to improve photoresponse. The x-spacing (see Figure 8) of the pixels is fabricated directly on each chip. The y-spacing of the pixels depends on the thickness of the chip wafers, which can range from 10 microns for ultrathin wafers to 300 microns or more for "standard" wafers. A lenslet array with off-axis lenslets can be used to effectively decrease the y-axis pixel spacing (while increasing the x-axis spacing).

Alternatively, a separate imager such as a backside thinned, or silicon-on-sapphire imager, can be directly indium bumped to edge-sensitive CCD input zones of the stacked 3-D CCD memory cube. CID image sensors can be readily bumped to respective charge mode detectors on the stacked memory chips, and accordingly are desirable sensors for such 3-D bumped imager arrays. Because the photosites are clocked directly in parallel to the corresponding CCD memory channels, the bump-mounted imager can be operated at very high frame rates corresponding to the 1 - 10 Mhz rate of the memory CCD channels.

Bump-mounting of a silicon-on-sapphire imager to the 3-D CCD memory stack permits closer y-pixel spacing when "thick" wafers are stacked. For example, by multiplexing 8 pixels of a bump-mounted imager to each CCD memory channel of a "stack" of 200 micron thick CCD memory chips, a 25 micron pixel spacing is produced. For 1K-long CCD memory channels, this provides memory storage for 125 full frames of the image for 2K long CCD memory channels, 250 full frame images can be stored in the 3-D array, which for a 512 x 512 imaging array multiplexed onto 64 stacked chips, constitutes a memory capacity of over 65 megabytes.

As shown in Figure 9, bump-mounting may also be used for interconnects at the output face of the imager/memory cube. This permits separate control of

high-speed imager drivers, high-speed CCD memory channel drivers, and slower speed output drivers. The compact, stacked geometry is suitable for operation in triggered burst mode, in which a triggering event initiates high-speed image capture and storage of 1,000 or more image frames in the analog CCD memory along the "z" axis. The 1,000 or more frames of image data may then be clocked or "read" out for processing at a second, slower data rate.

The stacked z-axis CCD memory chip geometry of this disclosure has advantages of full design efficiency for true parallel operation, separate imager, memory and output driver connection capability, enormous functional compactness and 3-D density of operational circuitry, small size, light weight, compatibility with image intensifiers and fill-factor enhancing lenslet arrays selectability of "good" chips for further assembly in defect-free larger array, and high yield fabrication of simple CCD memory chips with one linear imager array.

X-axis pixel separations are fabricated on-chip. However y-axis tolerances are subject to wafer thickness and stacking uniformity, while z-axis tolerances are subject to wafer die-cutting and alignment tolerances. Precise deep-etch techniques such as the "black silicon" vertical etching technique are used as opposed to wafer-saw techniques to separate the CCD dice for stacking, and to avoid silicon lattice damage which would result in excessive dark current ["The Black Silicon Method", H. Jansen et al., J. Micromech. Microeng. 5, pp. 115-120 (1995)]. Various alignment methods, including "pillar-recess" stacking as shown in Figure 10 and optical flat assembly may be used for z-axis alignment.

Bonding of even deeply grooved silicon wafers is easily accomplished using photoresist or anode

bonding of silicon wafers with a thin layer of photo-resist or R.F. sputtered glass at temperatures of less than 450° C. A processing potential of about one volt is sufficient to anode-bond silicon wafers with glass layers of less than 100 nm. [V. Spiering, et al., "Sacrificial Wafer Bonding for Planarization After Very Deep Etching," Journal of Microelectromechanical Systems, Vol. 4, pp. 151-157 (1995)].

Appropriately aligned mirror-polished silicon surfaces may also be bonded (in a monocrystalline manner) by wafer bonding techniques in which surface silanol groups dehydrate and remaining oxygen atoms dissipate at elevated temperatures. Low temperature bonding methods have recently been developed for Si/Si bonding at temperatures of less than 400° C., which may be suitable [Q. Tong, "Low Temperature Wafer Direct Bonding," Journal of Microelectromechanical Systems, Vol. 3, pp. 29-35 (1994)], and may be attempted for bonding of frontside mounting posts to the wafer backside, such as shown in Figure 7.

The heat dissipation of a single CCD memory chip operating at 1 Mhz clocking rate using low-resistance aluminum clock electrodes is typically about 2 watts, and a 3-D "stack" of 512 such chips will accordingly generate heat at about 1000 watts in a 2 cm. cube. This heat output is controlled by (a) designing the drive circuitry to only operate while the imager is functioning (e.g., the total heat for 1,000 frames at 1 megaframes/second is less than 0.001 x 1K watts = 10 watts), and (b) removing the heat using a 3-D internal coolant network. The high-volume density of circuitry generates significant heat, which may be removed by passive integral heat pipe or forced coolant flow. As shown in Figure 10, a pillar positioning chip-stack may be cooled by a coolant-flow system through the y-z

plane. Similarly, the CCD memory channels, being narrower than the imager pixels, can accommodate through-chip coolant holes etched on-chip by the deep-etching parallel-wall techniques used for micro-mechanical device fabrication and chip separation.

Microheatpipe arrays may be used as efficient backside heat spreaders or removers, by reducing the thermal path between the frontside heat sources and a thermal sink [A. Mallik, "Fabrication of Vapor-Deposited Micro Heat Pipe Arrays as an Integral Part of Semiconductor Devices," Journal of Microelectromechanical Systems, Vol. 4, pp. 119-131 (1995)]. Sealed microheatpipe arrays may be fabricated on the back side of thicker chip wafers as wickless, noncircular channels with a cross sectional hydraulic diameter of 10 - 50 microns, and a length of up to 2 centimeters. As little as two percent surface coverage produces a 40% increase in heat removal. Even greater heat removal can be accomplished by forced liquid circulation through the chip stack.

The compact 3-D stacked design may be used with conventional image intensifiers, and by using lenslets, a fill factor of 80% or more can be provided. The design is also fully compatible with image intensifiers which produce a direct electron output, by using electron-absorbing edge-sensitive input "pixels". Application of this electron bombarded sense mode can provide an effective optical gain of about 5000:1 over conventional CCD imagers.

It will be appreciated that although various aspects of the invention have been described with respect to specific embodiments, alternatives and modifications will be apparent from the present disclosure, which are within the spirit and scope of the present invention as set forth in the following claims.

WHAT IS CLAIMED IS:

1. A solid state imaging array comprising an array of photodetectors having locally associated therewith a storage plurality of sequentially operable analog memory cells, capable of high speed successive imaging.

2. A solid state imaging array in accordance with claim 1 in which the locally associated memory cells are linearly associated with each photosite along a CCD charge transport channel.

3. A solid state imaging array in accordance with claim 1 in which the photodetectors are arranged in a two dimensional imaging zone, and at least some of the analog memory cells associated therewith are oriented with a directional component orthogonal to the two dimensional imaging zone to form a three dimensional imaging and storage assembly.

4. A solid state imaging array comprising an array of photodetectors having associated therewith local memory wherein said array may be scanned at a first rate and at a second rate to provide an effective first frame rate and an effective second frame rate with exposure duration control.

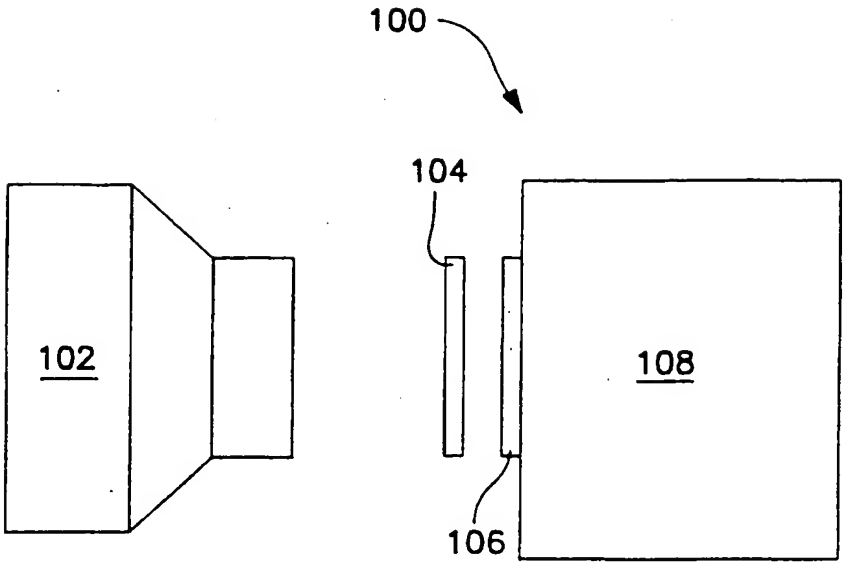


FIG. 1

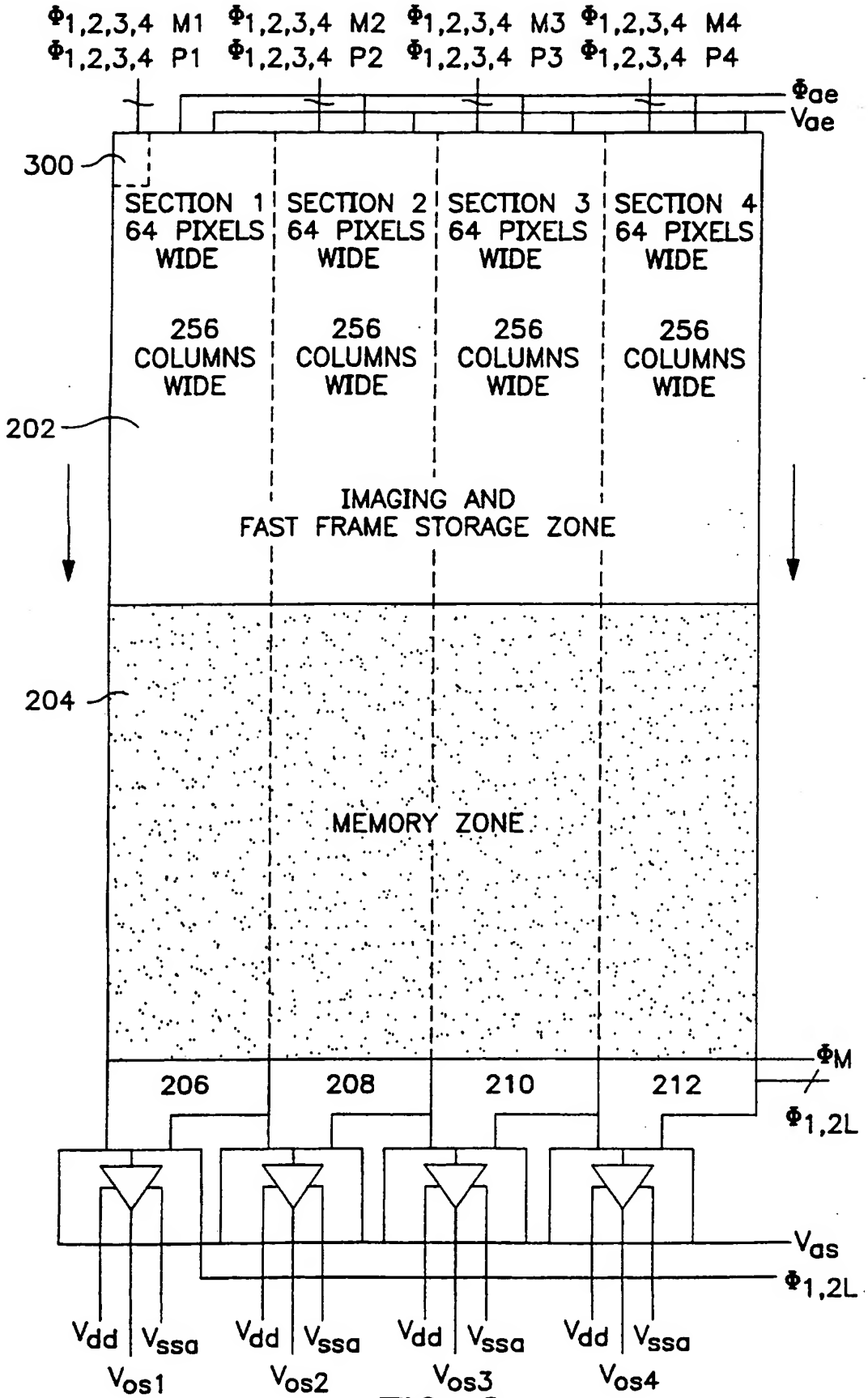
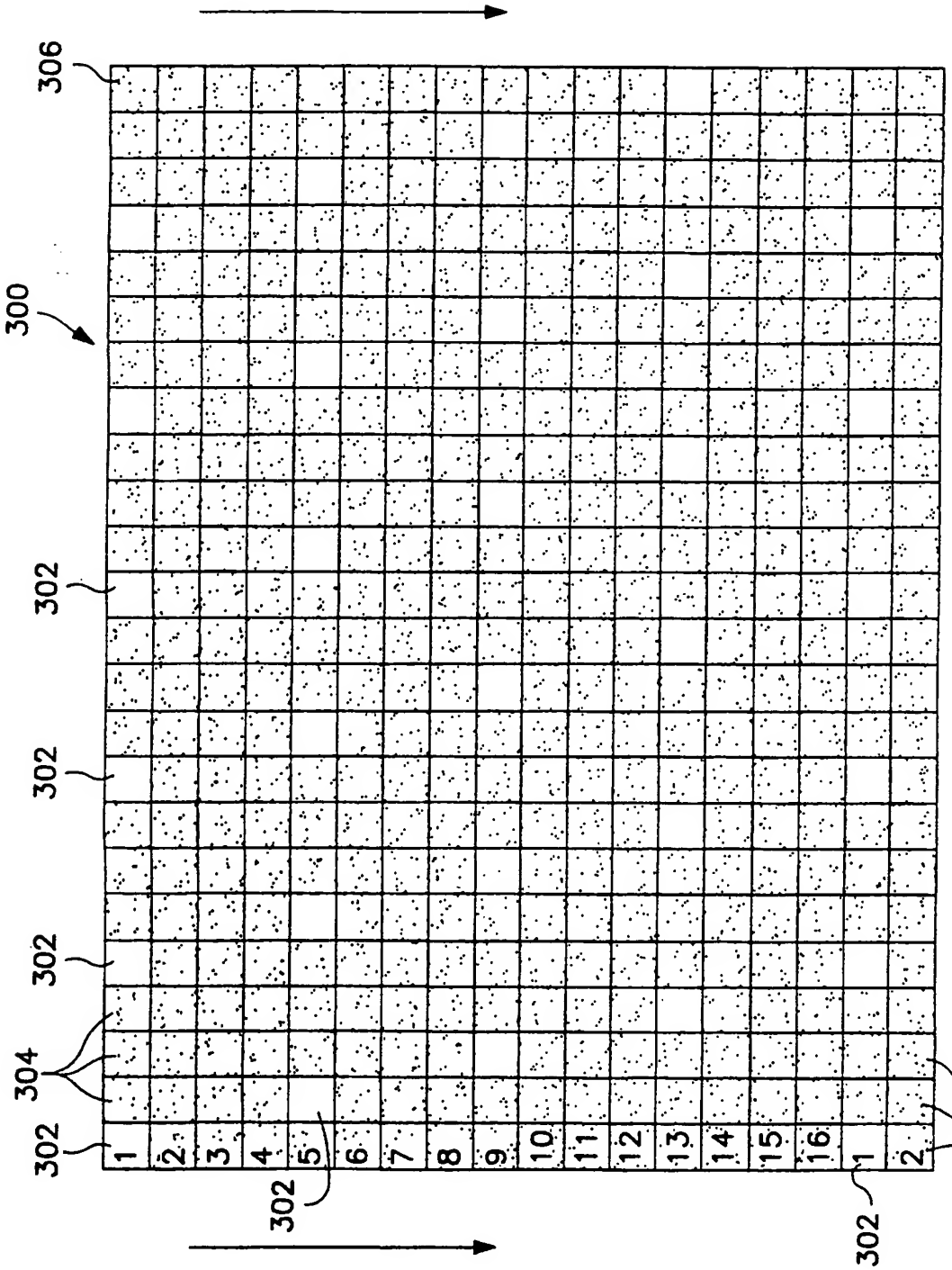

Φ1,2,3,4 M1
Φ1,2,3,4 M2
Φ1,2,3,4 M3
Φ1,2,3,4 M4
Φ1,2,3,4 P1
Φ1,2,3,4 P2
Φ1,2,3,4 P3
Φ1,2,3,4 P4
Φae
Vae
300
SECTION 1 64 PIXELS WIDE
SECTION 2 64 PIXELS WIDE
SECTION 3 64 PIXELS WIDE
SECTION 4 64 PIXELS WIDE
256 COLUMNS WIDE
256 COLUMNS WIDE
256 COLUMNS WIDE
256 COLUMNS WIDE
202
IMAGING AND FAST FRAME STORAGE ZONE
204
MEMORY ZONE
ΦM
206
208
210
212
Φ1,2L
Vas
Φ1,2L
Vdd
Vssa
Vos1
Vdd
Vssa
Vos2
Vdd
Vssa
Vos3
Vdd
Vssa
Vos4

FIG. 2


306
300
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302
302

FIG. 3A

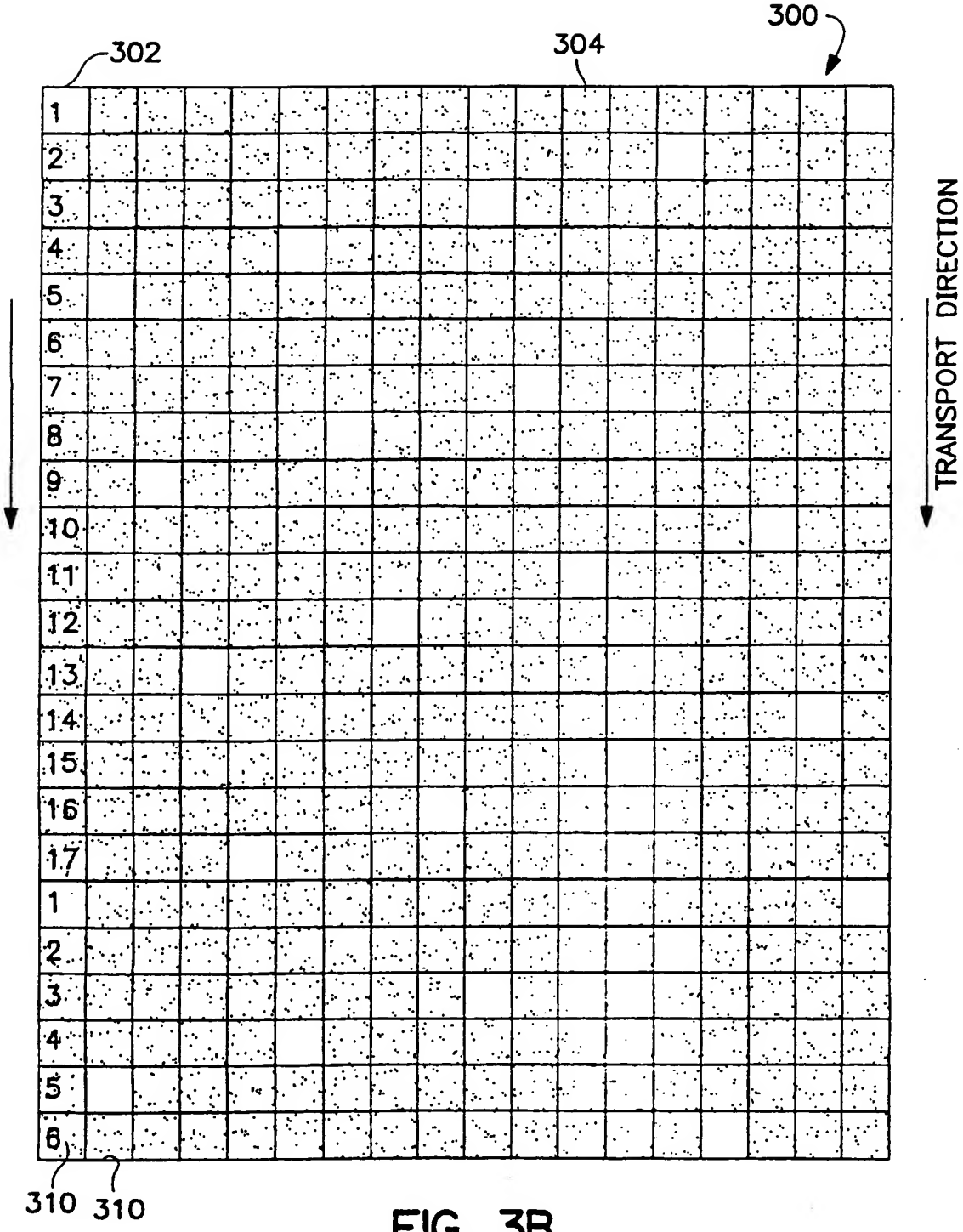
300
302
304
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
1
2
3
4
5
6
310
310
TRANSPORT DIRECTION

FIG. 3B

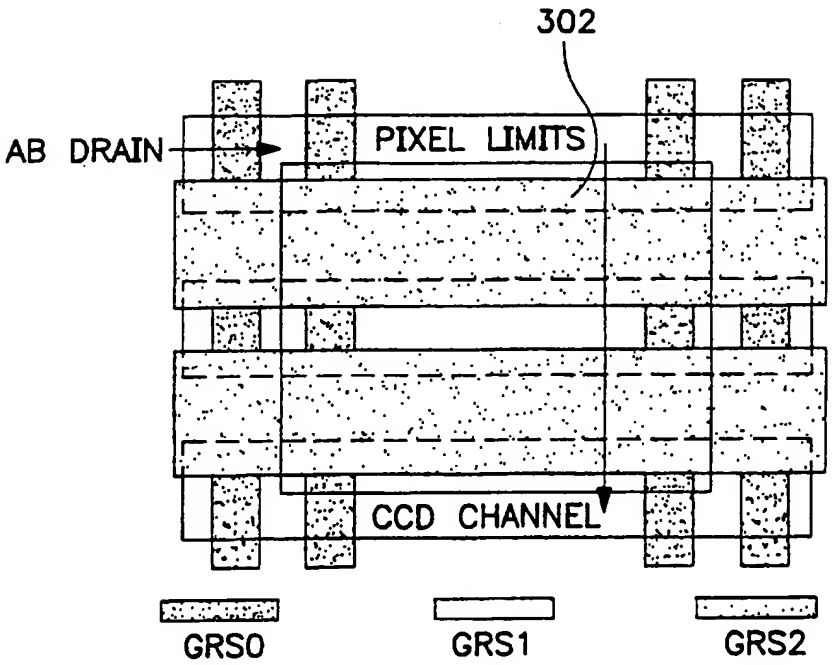

FIG. 4

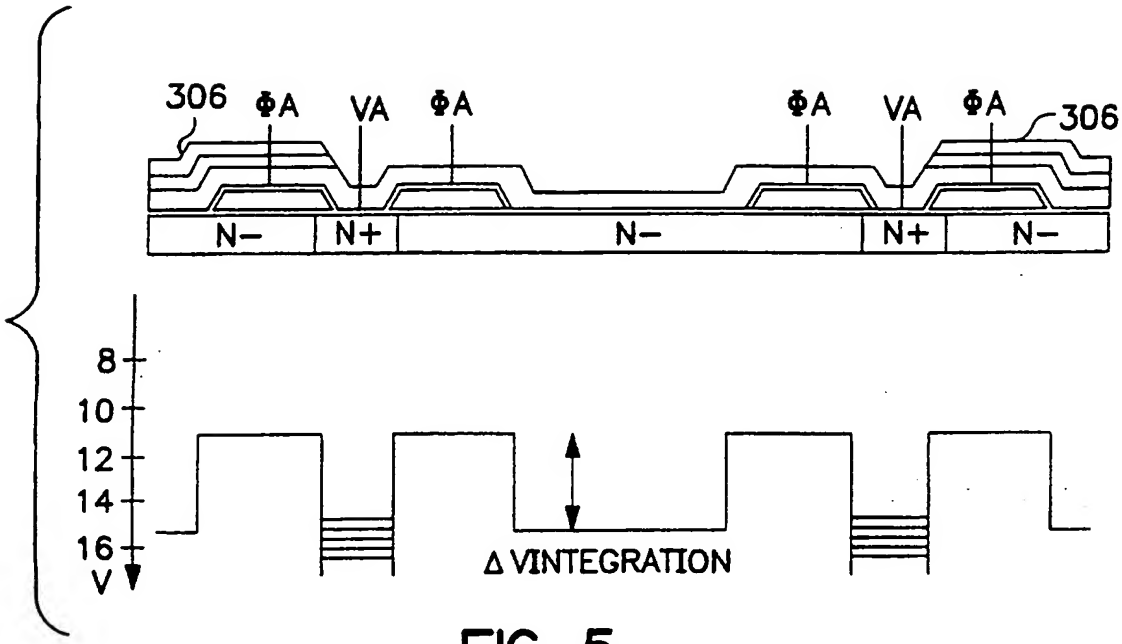
306
ΦA
VA
ΦA
ΦA
VA
ΦA
306
N−
N+
N−
N+
N−
8
10
12
14
16
V
Δ VINTEGRATION

FIG. 5

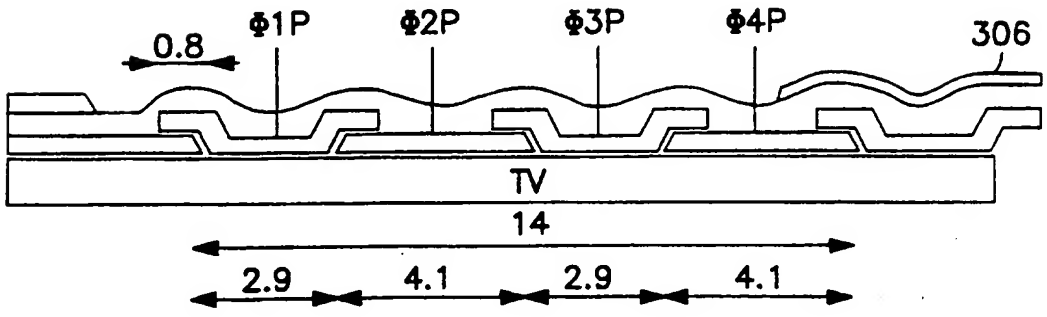
0.8
Φ1P
Φ2P
Φ3P
Φ4P
306
TV
14
2.9
4.1
2.9
4.1

FIG. 6

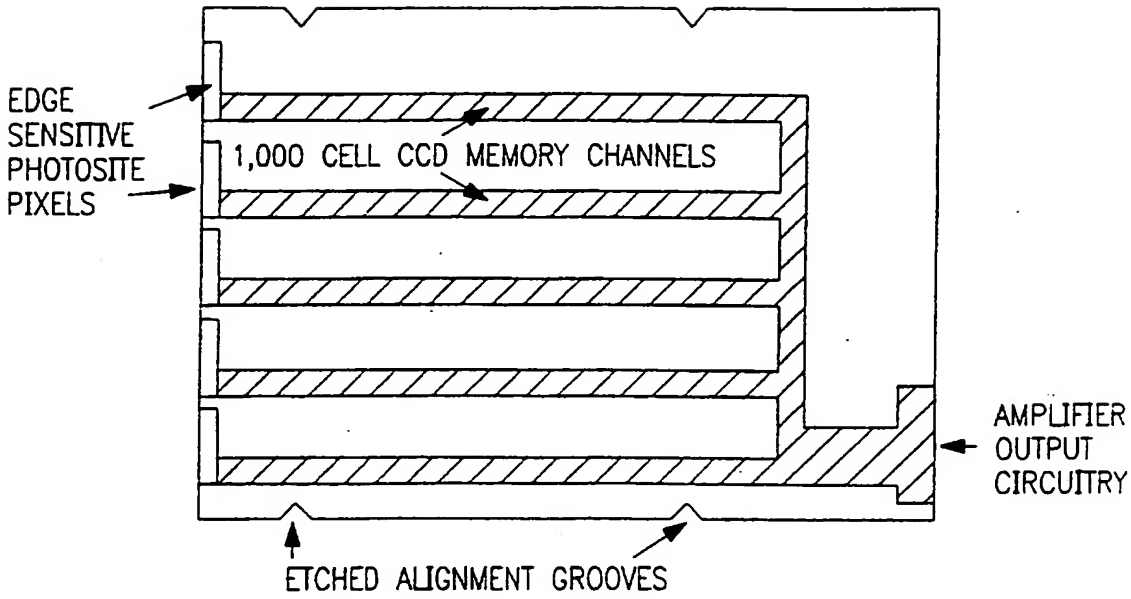
EDGE
SENSITIVE
PHOTOSITE
PIXELS
1,000 CELL CCD MEMORY CHANNELS
AMPLIFIER
OUTPUT
CIRCUITRY
ETCHED ALIGNMENT GROOVES

FIG. 7

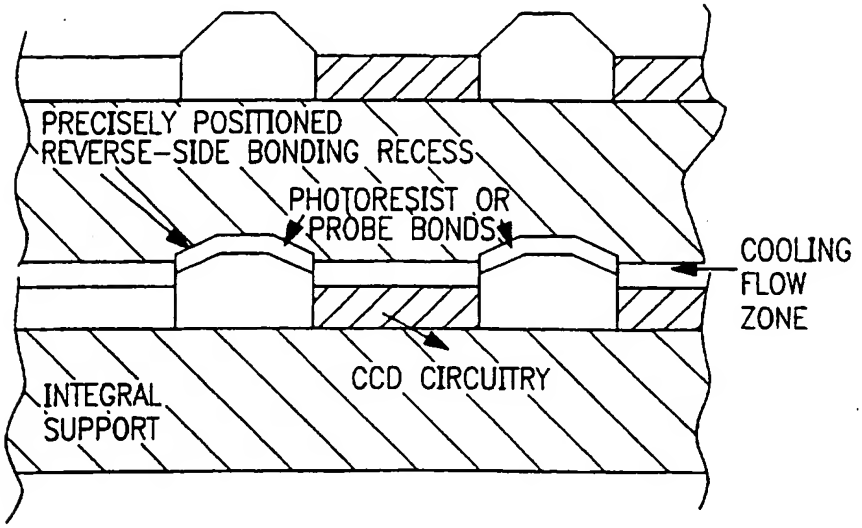
PRECISELY POSITIONED
REVERSE-SIDE BONDING RECESS
PHOTORESIST OR
PROBE BONDS
COOLING
FLOW
ZONE
CCD CIRCUITRY
INTEGRAL
SUPPORT

FIG. 11

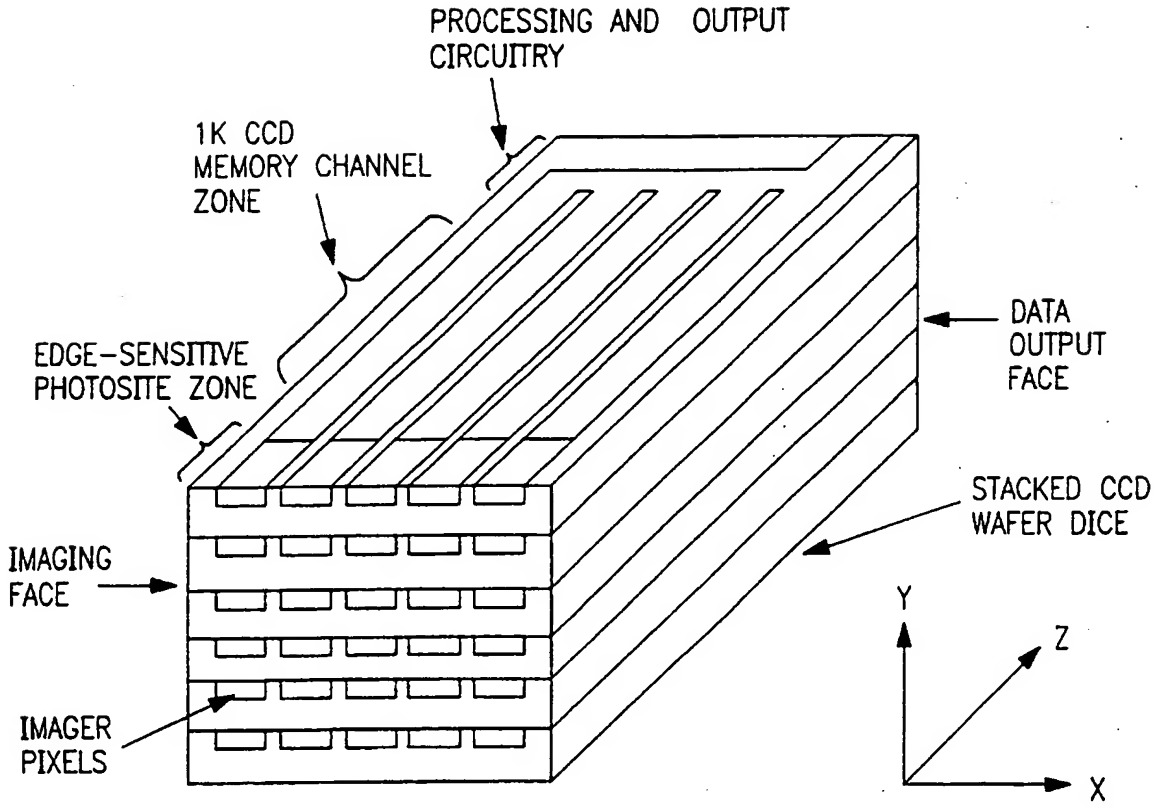
PROCESSING AND OUTPUT CIRCUITRY
1K CCD MEMORY CHANNEL ZONE
EDGE-SENSITIVE PHOTOSITE ZONE
DATA OUTPUT FACE
STACKED CCD WAFER DICE
IMAGING FACE
IMAGER PIXELS
Y
Z
X

FIG. 8

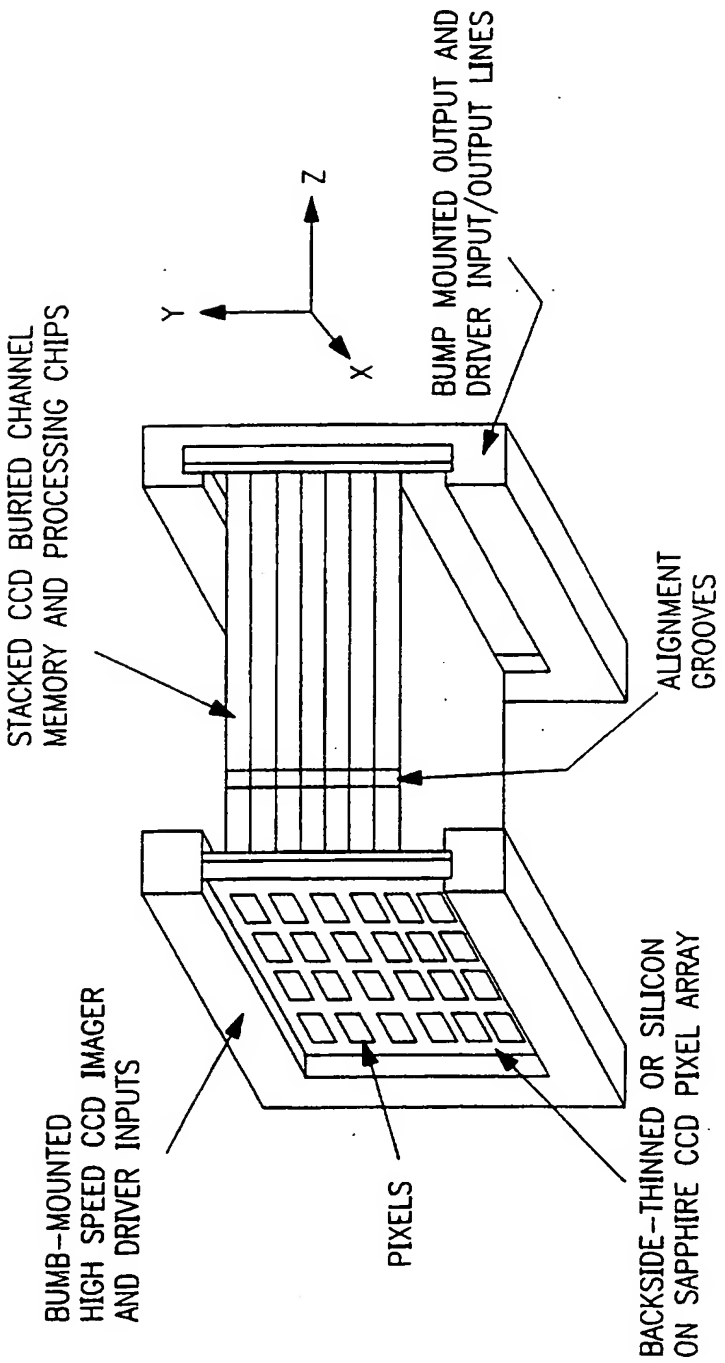
Z
Y
X
BUMP MOUNTED OUTPUT AND DRIVER INPUT/OUTPUT LINES
STACKED CCD BURIED CHANNEL MEMORY AND PROCESSING CHIPS
ALIGNMENT GROOVES
BUMB-MOUNTED HIGH SPEED CCD IMAGER AND DRIVER INPUTS
PIXELS
BACKSIDE-THINNED OR SILICON ON SAPPHIRE CCD PIXEL ARRAY

FIG. 9

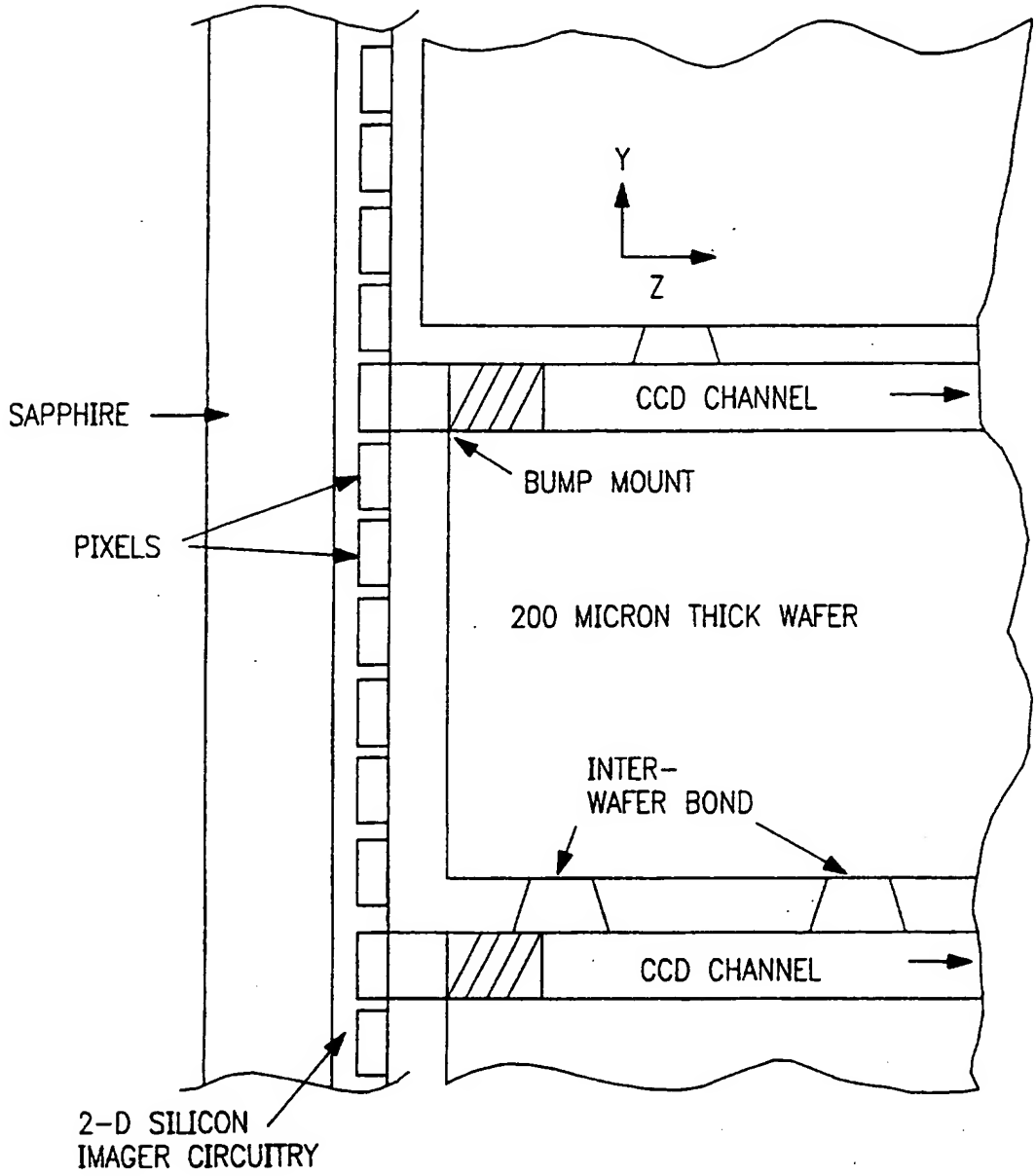
Y
Z
SAPPHIRE
CCD CHANNEL
BUMP MOUNT
PIXELS
200 MICRON THICK WAFER
INTER-
WAFER BOND
CCD CHANNEL
2-D SILICON
IMAGER CIRCUITRY

FIG. 10

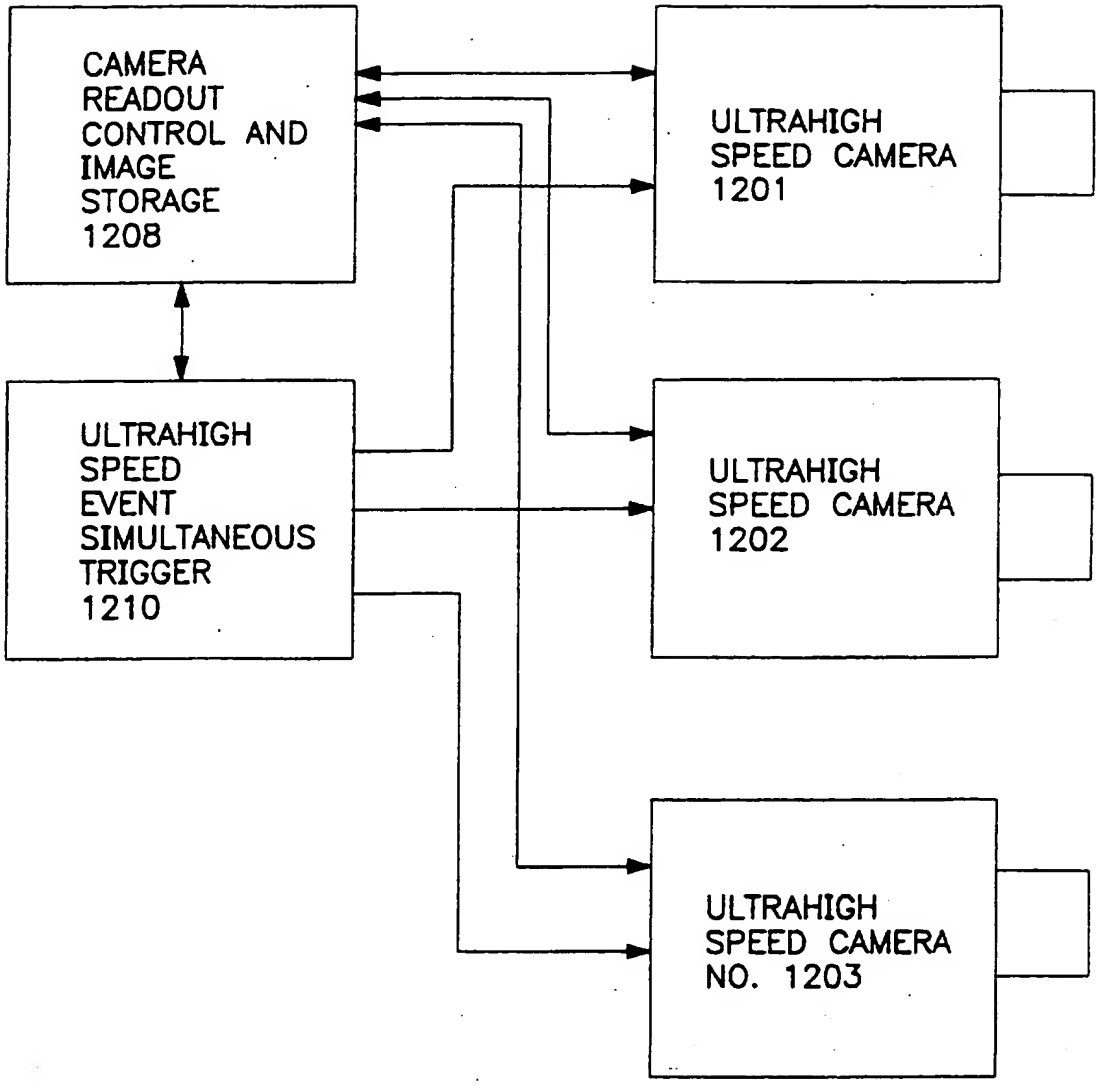
CAMERA READOUT CONTROL AND IMAGE STORAGE 1208
ULTRAHIGH SPEED EVENT SIMULTANEOUS TRIGGER 1210
ULTRAHIGH SPEED CAMERA 1201
ULTRAHIGH SPEED CAMERA 1202
ULTRAHIGH SPEED CAMERA NO. 1203

FIG. 12

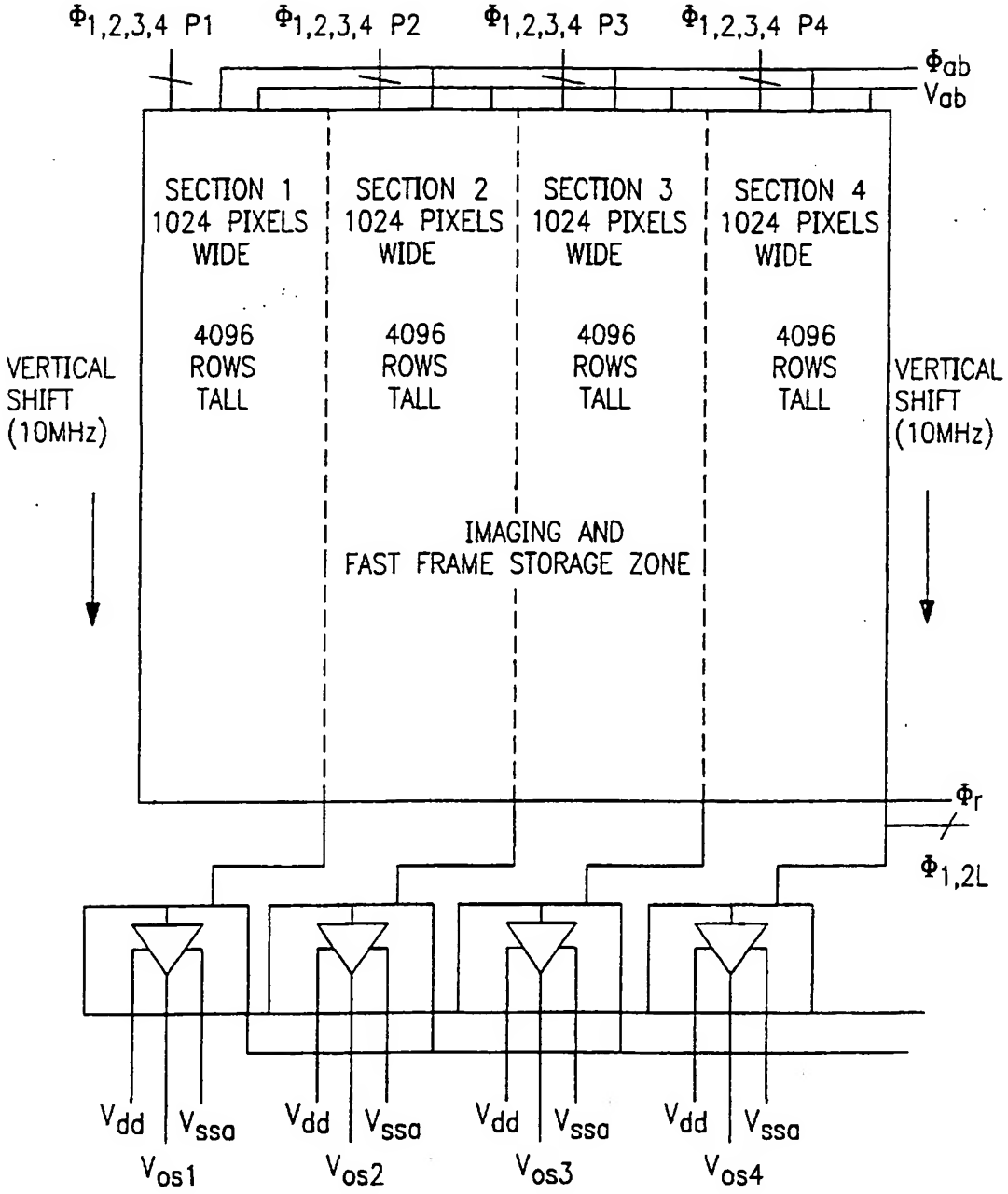
Φ1,2,3,4 P1
Φ1,2,3,4 P2
Φ1,2,3,4 P3
Φ1,2,3,4 P4
Φab
Vab
SECTION 1
1024 PIXELS
WIDE
SECTION 2
1024 PIXELS
WIDE
SECTION 3
1024 PIXELS
WIDE
SECTION 4
1024 PIXELS
WIDE
4096
ROWS
TALL
4096
ROWS
TALL
4096
ROWS
TALL
4096
ROWS
TALL
VERTICAL
SHIFT
(10MHz)
VERTICAL
SHIFT
(10MHz)
IMAGING AND
FAST FRAME STORAGE ZONE
Φr
Φ1,2L
Vdd
Vssa
Vos1
Vdd
Vssa
Vos2
Vdd
Vssa
Vos3
Vdd
Vssa
Vos4

FIG. 13

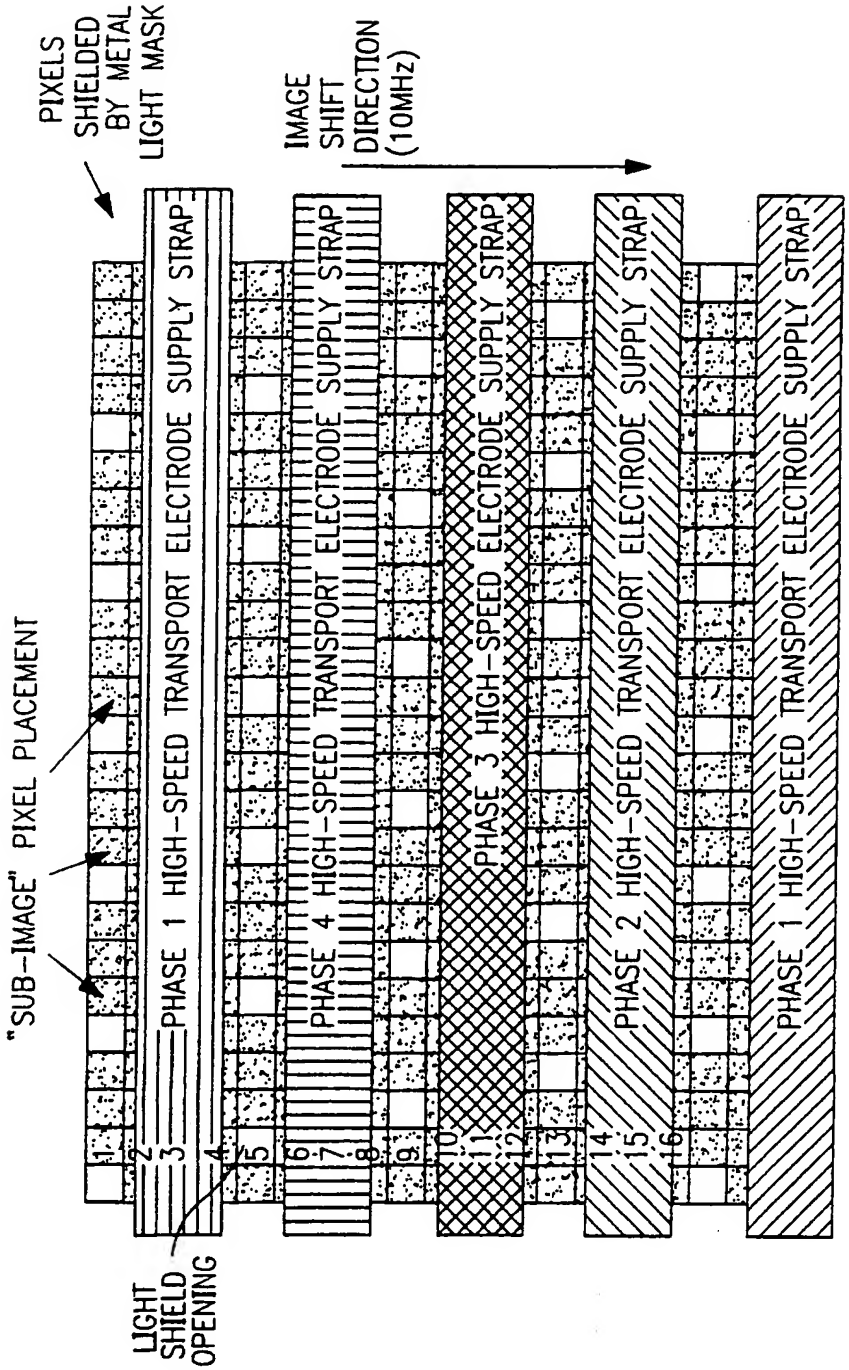
PIXELS SHIELDED BY METAL LIGHT MASK
IMAGE SHIFT DIRECTION (10MHz)
"SUB-IMAGE" PIXEL PLACEMENT
PHASE 1 HIGH-SPEED TRANSPORT ELECTRODE SUPPLY STRAP
PHASE 4 HIGH-SPEED TRANSPORT ELECTRODE SUPPLY STRAP
PHASE 3 HIGH-SPEED ELECTRODE SUPPLY STRAP
PHASE 2 HIGH-SPEED TRANSPORT ELECTRODE SUPPLY STRAP
PHASE 1 HIGH-SPEED TRANSPORT ELECTRODE SUPPLY STRAP
LIGHT SHIELD OPENING
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16

FIG. 14

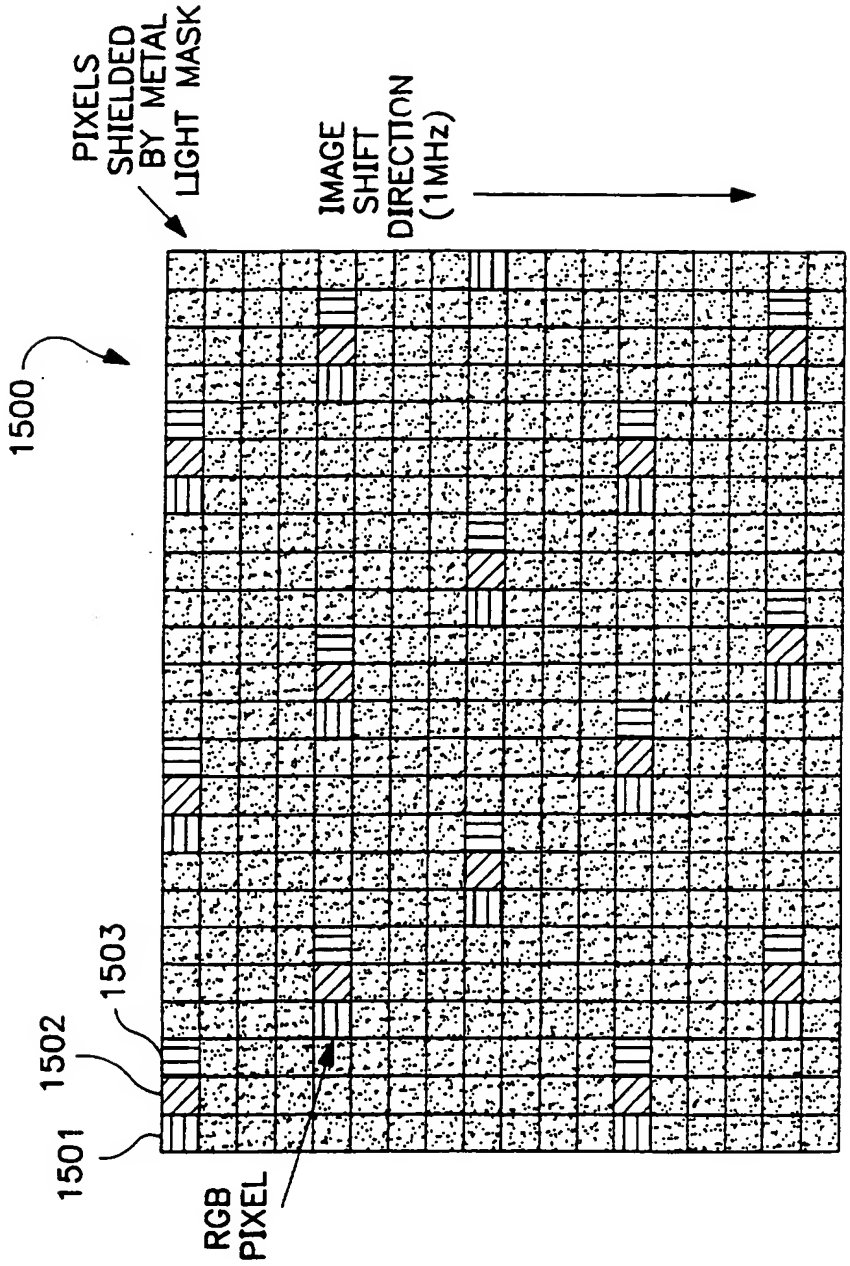
PIXELS SHIELDED BY METAL LIGHT MASK
IMAGE SHIFT DIRECTION (1MHz)
1500
1503
1502
1501
RGB PIXEL

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/07762

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :H04N 3/14, 5/335
US CL :Please See Extra Sheet.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 348/294, 296, 297, 298, 311, 312, 315, 316, 317, 319, 320, 322, 324

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,547,677 A (PARKER) 15 October 1985	1-3
A	US 4,758,895 A (ELABD) 19 July 1988	1-3
A	US 5,055,930 A (NAGASAKI ET AL) 08 October 1991	1-3
X	US 5,162,914 A (TAKAHASHI ET AL) 10 November 1992, col. 6, lines 15-68, col.11, lines 2-60.	4
X	US 5,355,165 A (KOSONOCKY ET AL) 11 October 1994, col. 4, line 6 to col. 6, line 45.	1-3
A	US 5,463,421 A (DEGUCHI ET AL) 31 October 1995.	4

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
01 OCTOBER 1997	31 OCT 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer VU, NGOC-YEN Telephone No. (703) 305-4946

Form PCT/ISA/210 (second sheet)(July 1992)★

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/07762

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

348/294, 296, 297, 298, 311, 312, 315, 316, 317, 319, 320, 322, 324